Fear and loathing: the modulatory affect of stress on memory formation and its wildlife management implications.

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Abstract

An ongoing challenge for wildlife managers is that target species habituate to or forget about hazing, even though the animals must be somewhat stressed by the hazing. Although stress and efficient memory formation/retrieval are considered to be incompatible, research suggests that the effect of stress on memory is complex. Mild and intense stress can impair memory formation and chronic stress can disrupt memory retrieval. Intermediate stress, however, actually enhances the formation of new memories, particularly long-term memories. Unfortunately, these conclusions are based data from only a very few domesticated species under highly controlled conditions. In nature the variation in baseline stress levels of animals are caused by differences in food availability, reproductive state, social standing, and other factors. Our current understanding of the effects of natural stress and hazing on wildlife is inadequate. We need research on wild animals, particularly under field conditions to understand the interaction of natural and human produced stresses. Such knowledge will help managers fine-tune their hazing efforts to maximize the long-term benefits of keeping birds away from airfields.

Introduction

One of the problems facing wildlife managers is that target species appear to habituate to hazing or other aversive management tools. Animals might not learn about or become accustomed to aversive experiences. As a result, the techniques lose their effectiveness, sometimes completely. A challenge for managers is to improve their ability to “teach” animals to perform certain behaviors, such as staying away from airports or choosing foods other then those that are valuable crops. Researchers have used psychological and neuroendrocrine techniques to examine how animals learn and remember experiences; one result gleaned by these researchers is that too much or too little stress decreases the efficiency with which animals learn and remember experiences,

particularly aversive experiences. This knowledge can lead to the development of improved applications of hazing and other aversive techniques.

The idea that stress modulates learning has an evolutionary advantage makes intuitive sense. It's important for an animal to pay attention to stressful events and to remember them in order to survive. For example, an animal may only get one chance to learn how to get away from a predator, so learning must occur quickly and efficiently, and the encoded memory must be robust. If we can reproduce the physiological state of a stressed animal we can "fool" the animal into learning something as if it was as critical as learning to avoid a predator.

Most of the experimental data currently available has been taken from studies using day-old chicks or rodents. The use of the chick as a model for exploring biochemical influences on learning grew out of imprinting studies, and followed reports that corticosteroid levels change during the critical period for imprinting (Weiss et al. 1977). The utility of day-old chicks as a model for learning studies lies in several factors. They are convenient to obtain and they perform an innate, discrete pecking behavior. Like other members of their order, chicks are precocial, and at one day of age they are active, learning organisms. Another benefit to using newly hatched birds is that there is little chance that they will have learned anything from their previous life experiences. The drawbacks to using chicks are the same as those involved in any study of young animals: it can be difficult to disentangle developmental processes from those more causally related to learning and memory. In young animals, changes occur in the nervous system as a result of growth, maturation, sensory stimulation, and sexual development. In chicks, for example, corticosterone naturally increases during the first few days of life, probably corresponding with the end of the sensitive period for imprinting. At the same time, major restructuring of the brain occurs. This makes it impossible to establish whether changes in the brain are a result of experimental manipulations, normal developmental processes, or interactions between the two. In adult animals, changes in the brain are minimal, although seasonal hormonal fluctuations are associated with changes in certain areas of the brain in some species. Therefore, we can't necessarily conclude that the results of studies conducted using chicks can be extrapolated to adult animals.

Despite some data interpretation problems in experiments involving very young animals, the advantages of using young animals have made them popular for investigating the effects of learning on the avian brain. Avoidance tasks are typically used, since they are rapidly learned and compatible with investigating neural processes in stressed animals. In the chick the avoidance task most commonly employed is one that takes advantage of the young birds' tendency to peck at brightly colored beads, and pairs this behavior with an aversive stimulus such as a chemical irritant (e.g., methyl anthranilate coating on the beads) or illness (e.g., lithium chloride injected into the animal). In passive avoidance tasks, the role stress plays in learning is fairly clear and uncontroversial. For wildlife managers, "teaching" animals to perform appropriately in a "passive avoidance" task is often a goal; consequently the information that has been gained through laboratory passive avoidance studies can be informative and useful.

Although most of the research has been on avoidance learning in day-old chicks, the results of other studies indicate that the same relationship between stress and memory can be present, but not in all cases. In mountain chickadees (*Parus gambeli*), a food-storing species, birds treated with corticosterone better remembered than untreated birds the locations of stored food items (Saldhana et al. 2000). Increasing corticosterone levels also influences behavior in natural situations. In red knots (*Calidris canutus*), unpredictable feeding schedules causes an increase in stress hormones (Reneerkens et al. 2002). Reneerkens et al. (2002) hypothesized that increased stress hormones might lead to an increase in foraging effort that can translate into useful knowledge for future foraging bouts. On the other hand, increased stress in the budgerigar (*Melopsittacus undulatus*) has been reported to interrupt a learned avoidance response to an acoustic stimulus (Lambert & VenMurthy 1986). Clearly, it is too early to conclude that the data collected from neonatal chicks can be extrapolated to free-ranging adult birds from other taxa and other learning paradigms.

Effects of stress on memory

The most common misunderstanding concerning stress and memory is the idea that stress interrupts learning and memory. This is only partly accurate. Chronic or severe stress can lead to memory attenuation and sometimes even a complete disruption of learning. Similarly, low levels of stress appear to have no modulatory affect on memory. Acute and moderate levels of stress, on the other hand, may enhance learning and

memory, depending upon the timing of the stressor with respect to the presentation of the learned stimulus (Fig. 1). The general learning theory explanation for this memory enhancement is that mild and acute stressful events trigger energetic responses or enhance motivation.

The physiological events that follow a stressful episode are well understood. Several hormones that are related to arousal, for example corticosterone (or cortisone in many mammals) and vasopressin have been studied to understand how they affect learning. In the day-old chick, the functional link and relationship between stress and memory has been particularly well-described. Chicks avoid beads coated with a concentrated chemical irritant (100% methyl anthranilate, or MeA) for at least 24 hours after their initial experience. However, they forget that beads coated with a 10% MeA solution are repellent in less than 9 hours. Their memory of the repellency of the 10% solutions can be increased if they are stressed (using social isolation, for example) prior to or following their initial exposure to the 10% treated beads. When the birds are stressed, they avoid the 10% MeA-treated beads for at least 24 hours, just as though the beads had been treated with the 100% MeA solution. Similarly, if they are injected with cortisone following their initial encounter with the 10% MeA-coated beads, they also avoid the beads for at least 24 hours. At the other extreme, if the combination of the aversive experience and stress is too strong, long-term memory formation is inhibited. Thus, chicks that encounter 100% MeA treated beads and are also injected with cortisone forget their experience more quickly than chicks that encounter the same beads but receive control injections of saline. Birds that were trained with 100% MeA-coated beads were found to have mildly elevated cortisone levels, as were chicks subjected to the 10% MeA-coated beads paired with social isolation treatment. Finally, studies in which stress hormones were blocked with a drug, long-term learning by chicks was inhibited. The key to long-term learning and avoidance, then, is that either the aversive experience is strong enough on its own or is paired with additional stress-modulating factors to bring blood cortisone within some critical range (Rose 2000).

Mechanism

Stress hormones are believed to facilitate the formation of memory through at least two different avenues: their effects on blood glucose levels and via enhanced protein synthesis in the brain (Cahill and McGaugh 1996; Rose 2000). The stress hormone

epinephrine, in particular, elevates blood glucose levels. Glucose has been implicated in improved memory, showing a U-shaped dose-response curve similar to that seen for corticosteroids (Gold 1995), although the exact mechanism by which glucose enhances memory formation is unclear.

For long-term learning to occur, experimental evidence indicates that protein synthesis in the brain is necessary (Davis and Squire 1984). The adrenocortical hormones are hydrophobic and fat-soluble and are therefore able to pass through the blood-brain barrier and into the brain, then through the cell membrane into neurons. Once in the cell, these hormones directly influence protein synthesis by binding regulatory receptors in the cell. The receptors then escort the hormones into the cell nucleus, where they bind with hormone-binding elements on DNA and instruct the DNA to initiate protein synthesis. The proteins that are responsible for long-term memory include glycoproteins known as neuronal cell adhesion molecules, or NCAMs. These molecules strengthen the associations between pre- and post-synaptic membranes of nerve cells, thereby promoting more permanent communication among the cells (Fig. 2). These connections between cells are believed to underlie long-term memory formation. Drugs that block protein synthesis, such as anisomycin, also disrupt memory formation. Experiments that follow the effects of blocking protein synthesis on memory suggest that there are two separate waves of synthesis. In birds, injections of the blocking agent immediately prior to or up to an hour after training disrupt learning, as do injections that are given during a window between 4 and 5 hours after training. Injections of the blocker between and 1 and 4 hours following training do not disrupt learning. The connection between corticosteroids and protein synthesis has also been demonstrated by the report that chicks injected with steroids that did not receive training had higher levels of glycoproteins such as NCAMs in the brain (Sandi and Rose 1997). Similar results have been documented in mammals, except that there are slight differences in the timing of the second wave of protein synthesis.

Chronic or severe stress, in contrast, disrupts memory formation, sometimes completely, resulting in amnesia. For example, rats stressed with brief handling for a period of 13 days had spatial memory comparable to that of control rats, while rats handled for 21 days were memory-impaired (Luine et al. 1996). Severe stress is implicated in the cognitive deficits observed in human post-traumatic stress syndrome. Chronic stress

causes both a chronic release of hormones and deficits in the immune system, and these factors appear to interact to cause structural damage to brain tissues (McEwen 2000). The mechanism by which severe, acute stress can lead to long-term changes in the brain is still poorly understood, but recent evidence suggests that stress hormones may cause long-lasting changes in neurotransmitter synthesis (Kaufer et al. 1998, Meshorer et al. 2002).

The studies reviewed above can be summarized as follows:

- stressors can facilitate the formation of long-term memories, but to facilitate long-term memory formation the stress needs to be both moderate in intensity and short-term.
- these general properties are known to hold true for for birds and mammals.
- the relationship between stress and learning is most convincing in avoidance learning.

Understanding the relationship between stress and learning is therefore a tool that can be exploited by wildlife biologists seeking to use nonlethal controls and keep birds and wildlife from specific locations such as airports. How to most effectively use this tool remains unexplored.

Types of stress

The types of stress typically employed in the laboratory setting are those that are most convenient to use. Some are promising tools for wildlife managers, but others probably will not be useful. Social isolation, handling, or injection of hormones, for example, are obviously not suitable for use with free-ranging animals and large populations. Food deprivation is rarely practical, and is detrimental to the target species. Food deprivation could have the undesirable effect of shifting animals' foraging to valuable crops.

Pain is stressful, and has been used to enhance the effectiveness of other methods – essentially putting "teeth" behind other stimuli by adding consequences to the cues. The effectiveness of painful repellents could be improved by adding additional stress to the animal. Methyl anthranilate is already used in the field as a bird repellent; data from studies on chicks suggests that the long-term effectiveness of this repellent can be improved by increasing the stress levels of animals exposed to the chemical.

Some stressors seem to vary in effectiveness across species. Many species become wary when an injured or dead conspecific is in view. One example is killing gulls as a reinforcer to using pyrotechnics at airfields and landfills. Similar to pain, the opportunity to see the consequences of a cue may be strong reinforcement for behavior when used skillfully.

Novelty should be considered a potential tool for wildlife management, and is occasionally applied in the laboratory as a stressor. Many species find novel items aversive, and this aversion causes physiological changes that are similar to those caused by stress. Novelty effects should be taken into account when considering the overall setting in which target species occur. In the laboratory, every new apparatus is novel to the animal subjects, and this novelty adds to the overall stress levels of the animals. In contrast to free-ranging animals, the target species whose behaviors we seek to change are likely to be accustomed to the setting in which they live. This means that stressors used in the laboratory may have to be intensified to be effective in the field. Another type of "novelty" can be introduced to animals by changing the timing, spacing, and other variables that are part of the hazing technique. This is a known effective means to improve avoidance responses, when diligently applied.

Natural cues, or cues that exploit natural responses of target species, can increase cortisone levels in animals if used properly. For example, great tits (*Parus major*) presented with a model of an inescapable predator (a stuffed, rotating owl from which the birds could not move more than 3 m away) had elevated cortisone levels for at least one hour. The sight of a novel shrub or a cardboard box, or a stuffed owl presented to free-ranging birds, initially elicited similar behavioral responses but no hormonal changes (Cockrem & Silverin 2002). Cockrem and Silverin's (2002) data at least partly explains the failure of raptor effigies to control bird behavior. Careful presentation of naturalistic cues could be a memorable, aversive event, although clearly more exploration of this approach is needed.

Future directions and applications

Despite the large body of experimental work on stress, learning and memory, the focus of past research has been to understand the neurobiology of learning and memory. Few species have been studied, and most of these have been subjected to highly unnatural

situations. However, we know a great deal about how peripheral hormones interact with memory processes in the central nervous system. This body of knowledge leads naturally to additional studies with an eye for wildlife control applications. For example, little is known about how the memories of adult birds are affected by stressful situations. Studies on young birds cannot necessarily be extrapolated to adults. Furthermore, young chicks have lower blood cortisone levels than adults, so the threshold of stress needed to improve memory might be much higher than it would be for adult animals. Although adult birds do not undergo the dramatic developmental changes experienced by juveniles, they are subject to seasonal differences in hormone levels that can impact how much stress is conducive to forming long-term memories. Thus, the timing of wildlife damage with respect to the seasonal hormonal state of the target species needs to be considered and studied. Finally, few studies have measured the hormonal influence on memory in non-gallinaceous birds, and these have yielded ambiguous results.

Before any manipulations can be made, we require a better understanding of the natural stress levels of free-ranging animals. For example, birds are known to undergo daily (Bruener et al. 1999; Romero & Remage-Healy 2000), and seasonal (Dawson & Howe 1983) fluctuations in corticosteroid levels. Similarly, in some avian species there are developmental variations in endogenous steroid levels (Weiss et al. 1977). Corticosteroid levels also become elevated with increasing uncertainty in the food supply (Pravosudov et al. 2001, Reneerkens et al. 2002). It is important to note that behavioral responses to increases in corticosteroids changes with seasonal fluctuations in baseline levels of hormones (Bruener & Wingfield 2000). Therefore, specific manipulations may have different behavioral consequences depending on the time of year or time of day that they occur.

We also have little idea what effects our current repertoire of hazing tools has on the hormonal levels of animals. Some tools may appear to stress subjects, such as models of predatory species, when they have little actual effect. Valuable knowledge can be gained by conducting hormonal assays following treatment with various hazing methods.

At times management attempts have included the use of combinations of harassment devices. While these efforts are on the right track, they have been haphazard and lack a theoretical basis. The intensity of hazing must be “just right”: too little or too much

intensity will reduce learning and avoidance. By monitoring the stress levels of target species and correlating hormone levels with the effectiveness of various hazing techniques, we may be able to fine-tune our hazing efforts. For example, we need to understand which concentration of methyl anthranilate is effective by itself for long-term repellency, and which concentrations require additional stressful stimuli in order to be effective. A combination of a low (and economically practical) concentration of MeA with an aversive stressor should enhance long-term avoidance. One study to date supports this idea: grazing damage by snow geese was ameliorated when methyl anthranilate was combined with a visual cue (white paint) (Mason 1996). The effect of the MeA probably was enhanced by the novelty of the visual cue and remembered longer.

We need to establish whether and how stress and memory are correlated in wild-caught adult animals, gain a better understanding of natural levels and variation of stress in free-ranging animals, and compare the effectiveness of our management practices with stress levels in the targets. A more thorough understanding of how hormonal levels correlate with memory and avoidance will allow us to streamline the development of aversants and to improve their use in any situation. Complementary laboratory and field testing are necessary to reach these goals.

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Figure captions

Fig. 1. Functional relationship between arousal level and learning or memory. Low levels of arousal (e.g., barely awake) are not conducive to learning and remembering. Similarly, intense stimulation (e.g., extreme fear) is thought to block learning.

Fig. 2. Schematic representation of the major processes underlying neuronal activation, communication and long-term stable interaction. Information is transferred between neurons from the axon of one neuron to the dendrite of another; the axon and dendrite communicate at the synapse. While communication among cells can be rapid, subsequent intracellular events can lead to the synthesis of proteins that stabilize the connections between neurons. The level of protein synthesis is hormonally modulated, and corticosteroids, which cross the blood-brain barrier and pass into the cell body, are key players.

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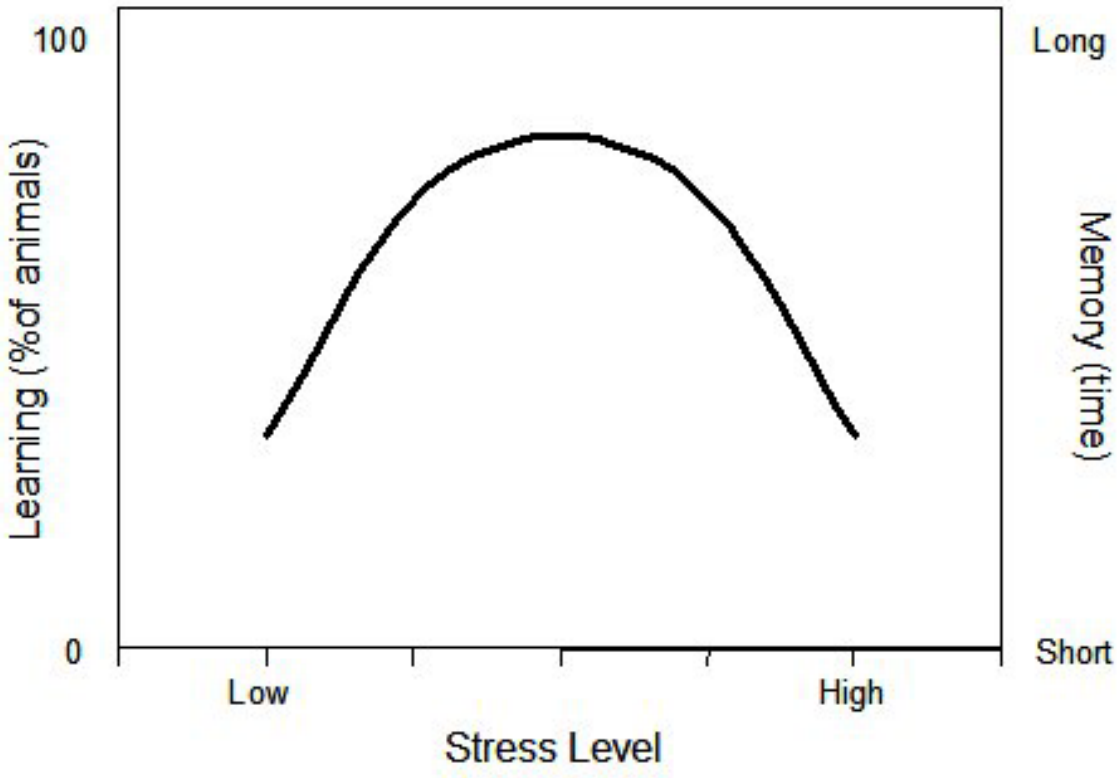
100
0
Learning (%of animals)
Long
Short
Memory (time)
Low
High
Stress Level

Fig.1

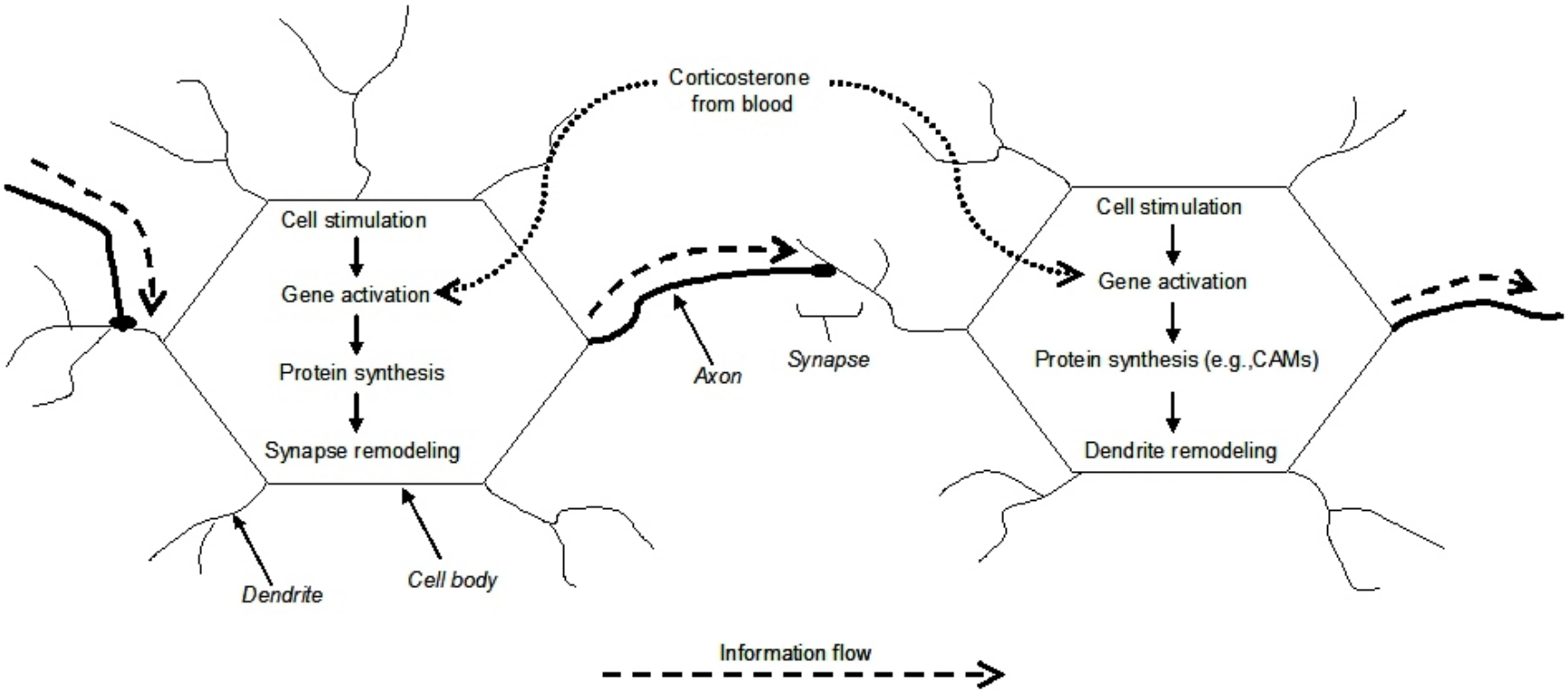
Corticosterone
from blood
Cell stimulation
Gene activation
Protein synthesis
Synapse remodeling
Axon
Synapse
Cell stimulation
Gene activation
Protein synthesis (e.g.,CAMs)
Dendrite remodeling
Dendrite
Cell body
Information flow

Fig 2